

Material flow analysis and energy requirements of mobile phone material recovery processes

Juan Manuel Valero Navazo · Gara Villalba Méndez ·
Laura Talens Peiró

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Abstract

Purpose Proper recycling of mobile phones and other electronic products is important in order to reduce the generation of large amounts of hazardous waste, lessen environmental and social problems associated to the extraction of minerals and primary production of materials, and also minimize the depletion of scarce materials that are often difficult to substitute. Current material recovery processes are used to recycle electronic waste of various compositions.

Methods Based on a review of the recycling processes and material flow analysis (MFA), we attribute the material and energy required to recover metals from 1 tonne of discarded mobile phones.

Results and discussion We estimate that the recovery rates of gold, palladium, silver, copper, nickel, lead, antimony, and tin from the recycling processes described are 80 to 99 % (16.4 % of the phone in weight). The two main industrial processes used at present time (pyrometallurgical and combined pyrohydrometallurgical) have similar energy consumptions (7,763 and 7,568 MJ/tonne of mobile phones, respectively). An average tonne of used mobile phones represents a potential of 128 kg of copper, 0.347 kg of gold, 0.15 kg of palladium,

3.63 kg of silver, 15 kg of nickel, 6 kg of lead, 1 kg of antimony, and 10 kg of tin as well as other metals that are not yet profitable to recover but might be in the future.

Conclusions We find that the energy consumed to recover copper from mobile phones is half of that needed for copper primary extraction and similar or greater energy savings for precious metal refining. Nevertheless, only 2.5 % of mobile phones arrive to industrial recovery facilities. There is a great potential to increase the amount of metals being recovered, thereby reducing energy consumption and increasing resource efficiency.

Keywords Electronic waste · Material flow analysis · Mobile phone recycling

1 Introduction

During this last decade, we have seen an unprecedented evolution of electronic devices that has brought important changes to our way of life. Every year, novel electronic products are launched. These new products aim to improve our quality of life and provide new experiences by incorporating new functionalities and design. However, the short lifetime of these products that comes as a result of a fast change in technology and overstimulated consumer behavior leads us to several unsustainable situations:

Large generation of e-waste Over the past years, the amount of electronic waste (e-waste) has quickly escalated to unforeseen amounts. UNEP estimates that between 20 and 50 million metric tonnes of e-waste is generated worldwide every year and expects this estimate to rise to 40–70 million metric tonnes by 2015 (UNEP 2006). Electronic products often contain toxic materials such as mercury, cadmium, lead, arsenic, dioxins, and furans, which if landfilled, incinerated, or

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J. M. Valero Navazo · G. Villalba Méndez
Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat
Autònoma de Barcelona, Campus de la UAB, 08193 Bellaterra,
Barcelona, Spain

G. Villalba Méndez (✉)
Department of Chemical Engineering, School of Engineering,
Universitat Autònoma de Barcelona, Campus de la UAB,
08193 Bellaterra, Barcelona, Spain
e-mail: gara.villalba@uab.cat

L. Talens Peiró
INSEAD Europe Campus, Boulevard de Constance,
77305 Fontainebleau, Paris, France

improperly managed, are released to the environment polluting air, soil, and water. A study on the toxicity potential of metallic elements in discarded mobile phones in China identified 12 metals as highly hazardous, of which the large amounts of lead in older phone models raised special concern (Wu 2008). The potential pollution from electronic disposal in landfills is a serious problem especially in countries with lax environmental regulations such as China, India, or Ghana. In these countries, informal recycling, also known as backyard recycling, is frequent (Rochat et al. 2007). The acids and cyanides used to dissolve the metals, together with toxic materials present in printed wire boards, are often poured to the ground or water. These so-called backyard operations often imply the burning of wires and plastic to liberate the metal components. Dark smokes containing dioxins created by the burning of the plastic flame retardants will cause serious health problems to the workers. The problem is worsened by the large flow of discarded electronic products from technologically developed countries to developing countries (Cobbing 2008; Kuper and Hojsik 2008; Puckett et al. 2002; Puckett et al. 2005).

Environmental and social impacts from the extraction of minerals The manufacturing of electronic devices requires special and precious metals such as gold, silver, palladium, tantalum, or niobium. These metals are found in quantities typically less than 0.01 % on Earth. As we continue to exploit these resources, the ore grades of these metals decrease, thereby requiring more energy for their extraction (Dominguez and Valero 2012). Furthermore, the extraction causes social and environmental impacts such as forced migration, conflicts to access minerals, landscape destruction, contamination from dust, or leaks of poisonous substances.

Material scarcity and supply risk Not only electronic products but also other technology products such as wind turbines, electric vehicles, and solar panels use precious and often scarce and nonrenewable materials. The demand of these substances has experienced an exponential increase that will continue and could lead to serious supply risk situations. Some of these elements can only be found in specific geographical areas. There are some countries that have absolute control in the production of some substances. For example, China has 95 % of world rare earth reserves, 83 % of gallium, 87 % of antimony, and 84 % of tungsten. The USA has 81 % of beryllium. Brasil has 90 % of niobium. South Africa has 77 % of platinum and 79 % of rhodium, and Chile has 60 % of lithium (OECD 2010). There are several reports published by the OECD and the European Commission analyzing the criticality of the different substances (European Commission 2010a, b; OECD 2010).

Current e-waste generation can be minimized in several ways. For example, raising public awareness for more

sustainable consumption could potentially increase the lifetime of products and minimize energy and material consumption from the production phase. Electronic production methods and practices could be improved to avoid toxic substances. Material recovery and recycling from e-waste can reduce material and energy consumption required by primary extraction and production and could furthermore lessen the dependency on producer countries and open opportunities for ensuring the supply chain.

In line with this last point, this paper aims to analyze today's best available technologies for material recovery from electronic waste—the pyrometallurgical process and a combined pyro-hydrometallurgical process. Based on these processes, a material flow analysis (MFA) for recycling 1 tonne of mobile phones is presented, including the energy consumption for these processes. Even though there is plenty of literature describing recoverable metal composition of electronic products (Huisman 2004; OECD 2010) and the recycling processes (Meskers et al. 2009; Hirschier 2007), we have not found a detailed MFA providing the inputs and outputs throughout the material recovery and recycling processes attributed to mobile phones. We have pieced this information from literature data, technical reports, and process descriptions. The analysis we present allows for comparison of energy and material requirements between recycling and primary extraction of the metals presently recovered from mobile phones. It also provides useful information for life cycle analysis (LCA) and resource efficiency assessment. We hope to add to the pool of knowledge in e-waste management and that these results can be used to further motivate policy and management for the recovery of mobile phones and promote efforts amongst electronic product designers, waste managers, and metallurgists to enable separation of waste into suitable feedstock for new products.

2 Background: mobile phone composition and waste preprocessing

The global annual sale of mobile phones is currently around 1,200 million units weighting 84,000 tonnes (excluding batteries) (OECD 2010). Based on a current mobile phone lifetime of 18 months (EPA 2004) (Villalba et al. 2012) and an annual increase of cellular phone subscriptions of 12–15 % (ITC 2011), we quickly realize the great magnitude of the waste generated and the stock of materials that are no longer in use. Where do these out-of-use cellular phones go?

There are several routes a discarded mobile phone can follow. Several studies coincide that 45–48 % of used phones are simply stored at home, and 23–30 % are either sold or traded in for a new phone (OECD 2010; Cobbing 2008; Villalba et al. 2012). The studies differ when comparing the number of cell phones that end up in a recycling plant, ranging from 2 % (figure given by Nokia but unclear if that accounts

for all cell phones or just Nokia brand) to 16 % (based on surveys conducted in the USA, UK, and Canada). According to Umicore, only 2.5 % of the mobile phones collected reach current best available technologies for material recovery (Hagelüken and Buchert 2008).

The material composition of mobile phones varies and depends on producers, functionalities of the device, and changes in communication technologies. Table 1 summarizes the quantity of different substances in mobile phones (excluding batteries) found in several studies. A recent study adds additional materials to this list, such as dysprosium (33 ppm),

niobium (38 ppm), and tungsten (up to 3 % because of its use in vibrators) (Villalba et al. 2012).

The recycling of mobile phones is driven by economic and environmental interests and limited by physical restrictions of the metallurgical processes of separation. Gold represents 80 % of the value of the materials in a discarded mobile phone, followed by 10 % from palladium and 7 % from silver. Recovery of other metals is only economically feasible at present for the content of these precious metals (Meskers et al. 2009). However, metals that are not economically feasible to recover right now could become so in the future if their

Table 1 Materials present in mobile phone given by different sources (Hagelüken 2007; Huisman 2004; OECD 2010; Oguchi 2011; Wu 2008). To go from percentage to parts per million, multiply by 10,000

			Huisman 2004	Umicore	OECD 2010	Wu 2008	Oguchi 2011
Organics		%	59.6	44	43	–	47
Glass		%	10.6	–	14	–	–
Iron	Fe	%	8	6.5	7	6.4	1.7
Aluminum	Al	%	2.9	1.7	5	12.1	0.6
Copper	Cu	%	14.2	12.9	13	8.7	12.8
Nickel	Ni	%	1.12	1.5	1	0.8	
Lead	Pb	%	0.3	0.6	1	0.2	0.5
Tin	Sn	%	0.7	1	1	0.6	1.3
Antimony	Sb	%	0.1	0.1	0.1	0.0	–
Silver	Ag	ppm	2,439	3,666	3,500	887	1,439
Gold	Au	ppm	382	354	400	166	568
Palladium	Pd	ppm	151	151	<200	49	114
Platinum	Pt	ppm		5	<100		
Beryllium	Be	ppm	33	88	<100	25	
Zinc	Zn	%	0.64	1		0.1	0.2
Magnesium oxide	MgO	%		3.4	3		
Calcium oxide	CaO	%		1.9			
Silica	SiO ₂	%		11.6			
Manganese	Mn	%		0.2		0.1	
Titanium	Ti	%		1.1		0.04	
Barium	Ba	%		0.8		0.10	0.7
Zirconium oxide	ZrO ₂	%		0.11			
Cerium oxide	CeO ₂	%		0.1			
Cobalt	Co	%				5.2	0.0
Chromium	Cr	%	0.34			0.7	
Neodymium	Nd	ppm				1,454	
Wolframium	W	ppm				7	
Bismuth	Bi	ppm	308			10	167
Arsenic	As	ppm	7			39	
Cadmium	Cd	ppm	0.2			2	
Mercury	Hg	ppm	0			0.1	
Gallium	Ga	ppm					53
Strontium	Sr	ppm					163
Tantalum	Ta	ppm					985

price increases. Some of the metals contained in mobile phones like palladium, rare earths, antimony, gallium, and niobium are considered critical in different reports (Buchert et al. 2009; British Geological Survey 2011; European Commission 2010b) because there is a potential risk supply that could threaten the development of technologies that depend on them.

Mobile phones are disassembled before reaching material recovery companies. The separation process can be done either by manual disassembly, mechanical shredding, or a combination of both. Mechanical shredding consists of a series of crushing processes that break up the material into smaller sizes. The shredded material is then sorted into different fractions based on different physical properties such as density and magnetism. The typical methods used are magnetic separation of ferrous parts, eddy current separation of nonmagnetic metals, and gravity separation. However, these automatic separation processes are not 100 % effective as physical properties can be affected by particle size or adhesion to surfaces. Thus, part of the precious metals end up in the aluminum and ferrous fractions or are lost as dust. Several studies show that 20 % of the precious metals is lost by mechanical preprocessing (Huisman 2004; Meskers and Hagelüken 2009).

Mechanical processes require relatively low operating costs and can process higher volumes of waste than manual dismantling, which entails separating the plastic cover, the battery, main body, and printed wire boards (PWB). Manual disassembly has lower environmental burden and higher recovery rates, but is very dependent on labor costs. The quality of the feedstock for the recycling process depends on how the disassembly is carried out. This operation is more commonly referred to as waste preprocessing.

3 Mobile phone material recovery

Material recovery of mobile phones and other electronic products basically follows the same refining processes used for the extraction of the metals they contain (such as copper, gold, or silver), avoiding the most energy-intensive stages in the production of metals which are mining and mineral ore concentration. Refining processes are typically divided into two groups: pyrometallurgical and hydrometallurgical processes. In pyrometallurgical processes, the raw material is heated and melted in furnaces at temperatures above 1,500 °C. At these elevated temperatures, mineral ores become relatively unstable, and the targeted metal is recovered by a series of metallurgical reactions. Hydrometallurgy, also known as leaching, consists on the selective dissolution of metals from their bearing materials. It involves the use of aqueous chemicals at much lower temperatures to dissolve the metal, which is then recovered from the solution by electrolysis or precipitation. In

general, metal recovery processes use both processes. The complete recovery process is not unique for each metal. There are many production routes that can be used to obtain a certain metal depending on the initial composition and form of the metal.

An important difference between pyrometallurgical and hydrometallurgical processes is that the first requires advanced technology for process optimization and large infrastructures such as integrated smelters and is only economically feasible at large scale. The infrastructure for these processes requires large economic investments. For example, the pyrometallurgical recovery facility of Umicore in Hoboken needed an investment of over US\$1 billion (Hagelüken 2006). On the other hand, hydrometallurgical process can be done at a very small scale. Just a few hand tools, a grinder, and some buckets with acids are enough to recover part of the copper and precious metals from electronic waste.

Since the recycling and the primary production of metals are very similar, it is no surprise that the recovery of metals from scrap is done by major primary metal producers. The best examples are Boliden (Ronskar, Sweden), Umicore (Hoboken, Belgium), Aurubis (Hamburg & Lunen, Germany) and Brixlegg (Austria), Xstrata (Canada), and Dow (Japan). They have adapted one or two of their primary processing plants to process electronic waste as well as other wastes containing valuable metals. They have had to make costly modifications to treat a more variable composition in the feedstock and install improved gas cleaning systems to remove polychlorinated and polybrominated dioxins and furans (PCDD/Fs and PBDD/Fs) released from the burning of brominated and chlorinated flame retardants contained in the plastics. For example, Umicore Hoboken plant in Belgium was refurbished with a 200 million € investment between 1997 and 2003, shifting Hoboken's focus from concentrates to recyclable materials and industrial by-products. One quarter of the costs cover installations for safety and environmental protection including particular air and water treatment facilities (Hagelüken 2006; Brusselaers et al. 2005). For these large facilities, recovery rates are high: 98–99 % for gold, between 90 and 99 % for silver and palladium, 99 % for copper, 85 % for nickel, 85 % for lead, and 80 % for tin (Huisman 2004; Keller 2006; Legarth et al. 1995).

4 Process description

All industrial recycling of mobile phones starts with the recovery of copper since it is the predominant metal (8.7 to 14.2 % by weight of cell phone), and it is a good collector of precious metals. Just like copper primary production, copper recycling is carried out by two main processes: the pyrometallurgical, normally used for sulfide ores (80–90 % of total production), and the hydrometallurgical, used for oxide ores

(10–20 % of total production). Many of the abovementioned companies (Boliden, Aurubis, Brixlegg, and Xstrata) use the conventional pyrometallurgical process that involves a smelter, converter, anode furnace, and electrolytic refining. Umicore uses a combination: a smelting phase followed by leaching and electrowinning processes. The different options for electronic waste recycling are represented in Fig. 1. The first smelting step is common to both recycling processes. Then, the pyrometallurgical route treats the resulting product from the smelter by conversion, anode casting, and electrolytic refining, whereas the combination process employed by Umicore continues with leaching and electrowinning. The final precious metal refining processes are common to both pathways. The following paragraphs describe the processes in more detail and quantify the material and energy flows.

To perform the MFA, the feedstock composition of 1 tonne of mobile phones given by Umicore in Table 1 is used since it is the most up-to-date (2007). The composition is the average of 11 batches of mobile phones weighting an average of 9.5 tonnes each (Hagelüken 2007). The study analyzes the material and energy flows necessary to recycle the metals from 1 tonne of mobile phone waste, starting with the mechanical shredding. Transportation and collection of the

mobile phones is excluded from the system, as well as any previous handling or dismantling.

4.1 Smelting

The process starts with mobile phones being fed to the copper smelter. In the real operating mode of the smelter, the composition of the feed is continuously changing. Various industrial wastes and by-products from other nonferrous industries (e.g., drosses, mattes, speiss, and anode slimes), as well as consumer recyclables such as car exhaust catalysts or printed circuit boards can be fed at the same time. As a reference, Umicore's Hoboken plant treats over 250,000 tonnes of different wastes per year, from which electronic waste presently covers up to 10 % of the feed (Brusselaers et al. 2005). However, for the purpose of this material flow analysis, we will consider the case in which the feed consists 100 % of scrapped mobile phones without their batteries and rear covers. In the real operating mode, feed composition is analyzed, and all following metallurgical processes are adjusted to maximize recovery efficiency.

In the case of primary copper ores or other scrap, flux, coke, and fuels are added to the smelting mix. However, in the

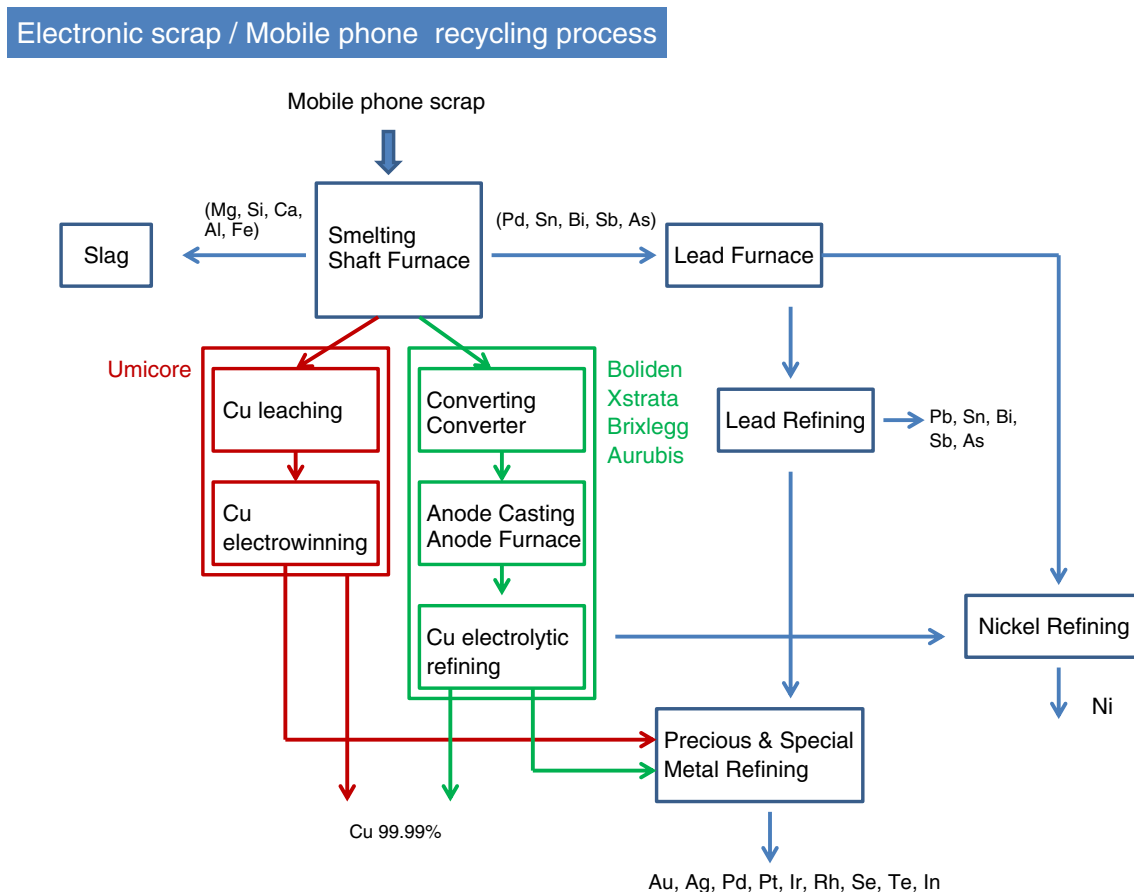


Fig. 1 Mobile phone material recovery process

case of mobile phones, the plastic they contain acts both as reducing agent and fuel. A study conducted by Umicore showed no differences on recovery rates or operating stability between running with coke as fuel or using the plastics in electronic waste. Moreover, the energy contained in the plastics is greater than the energy needed to smelt e-scrap, and for that reason, smelters are typically equipped with heat recovery systems. Umicore provides some data on this energy balance: the energy contained in the plastics of 1 tonne of mobile phones represents a total of 10,652 MJ. The energy needed for smelting this 1 tonne is 1,393 MJ¹ (13 % of the embodied energy) (Hagelüken 2007). Even if we include the additional 137 MJ/tonne necessary for the initial shredding (Hischier 2007), the result is a positive net energy balance (which is collected by heat recovery systems and used for the remaining refining processes).

The main function of the smelter is the effective separation of copper from lead and the concentration of the precious metals such as gold, silver, and platinum group metals in the copper phase. The primary product obtained from the smelter is the so-called black copper or copper matte with a copper content of approximately 80 %. The remaining outputs are the lead bullion, slag, and off-gases. Figure 2 shows the MFA for the smelting of 1 tonne of mobile phones, based on the Umicore process (Hagelüken 2007). One tonne of mobile phones results in 147 kg of black copper, 17 kg of lead bullion, and 396 kg of slag. The black copper fraction contains 128 kg of copper, 15 kg of nickel, 3.6 kg of silver, 347 g of gold, 151 g of palladium, and 5 g of platinum. The lead bullion contains 6 kg of lead, 10 kg of tin, and 1 kg of antimony. The total slag collected weighs 396 kg, being its main components silica (116 kg, coming from the plastic of PWBs), iron (65 kg), and aluminum oxide (47 kg). In the integrated smelter process, iron and aluminum are not recovered. Their recovery should be done at the preprocessing, which can result in a 20 % loss of precious metals.

By mass balance, we calculate approximately 440 kg of emissions for 1 tonne of shredded mobile phone waste, which cannot be too off course because the waste contains 44 % organic and plastic matter. In the smelting process, the plastics and epoxies contained in the mobile phones are combusted, giving off energy and gases. The exact composition of the emissions is difficult to calculate because it varies greatly on the composition of the feedstock. Ecoinvent gives the emissions allocated to the electronic scrap according to its share in the production of lead and copper for a Kaldo smelter (Classen

et al. 2009). However, the emissions are given on annual averages, and the Kaldo smelter is used mostly for lead production. Instead, we have included concentration values given by Umicore to give an orientation of the composition (Brusselaers et al. 2005). Off-gas dusts contain mainly zinc oxide, but also tin and lead oxides and some copper. These particles are captured and sent back to the smelter.

After the smelting, the following treatments can continue pyrometallurgically in a converter–anode furnace–electrolytic refining path or switch to a hydrometallurgical route consisting of leaching and electrowinning. In the first case, the resulting black copper is sent to the converter in liquid state. In the second case, it is granulated and sent to the leaching and electrowinning plant.

4.2 Pyrometallurgical route

The pyrometallurgical route consists of the following steps: converting, fire refining, and anode casting in the anode furnace and finally electrolytic refining. Figure 3 shows the MFA diagram for these operations. The converting process is typically done for primary copper sulfide ores to remove sulfur and some elements that have not been completely removed on the smelting phase (iron, lead, tin, zinc, arsenic, and antimony). Mobile phones do not contain sulfurs, so these processes are mainly done to extract these other elements. The converter operation is based on the oxidation of iron, lead, and other metals except for copper. An air/oxygen mixture is blown through the liquid matte recovered from smelting; the remaining iron and impurities are oxidized; and slag and gases are formed. The slag is skimmed off periodically, and the resulting product is typically called “blister copper.” A part from the liquid black copper charge, copper-rich scrap, is added at this stage, like the copper anodes coming from the electrolytic refining. The energy needed for the converting process ranges between 2.1 (US Congress 1988) and 3.1 MJ/kg of refined copper (Reuter et al. 2005). We use the average of 2.6 MJ/kg of refined copper. Taking into account that there are 192 kg of copper anodes produced from the converter and anode furnace, the energy required is 500 MJ/tonne mobile phones.

Blister copper from the converter is then taken to the anode furnace where it goes through two steps. First, the fire refining process removes the remaining oxygen by blowing natural gas or propane. Then, blister copper is cast into thin big plates that will be used for electrolytic refining. The energy needed in this step is 958 MJ (US Congress 1988; Reuter et al. 2005). Figure 3 shows the MFA for the converting, anode furnace, and electrolytic refining processes for 1 tonne of mobile phones. Air emissions have been calculated from Ecoinvent data on precious metal recovery from electronic waste (Classen et al. 2009). Unfortunately, Ecoinvent reports on

¹ A total of 7,431 MJ/tonne is necessary for smelting and refining 1 tonne of shredded mobile waste (Hagelüken 2007) of which 19 % is attributed to the smelting phase and 81 % to the rest of the refining processes (based on ratio provided by Meskers et al. (2009) given for e-scrap).

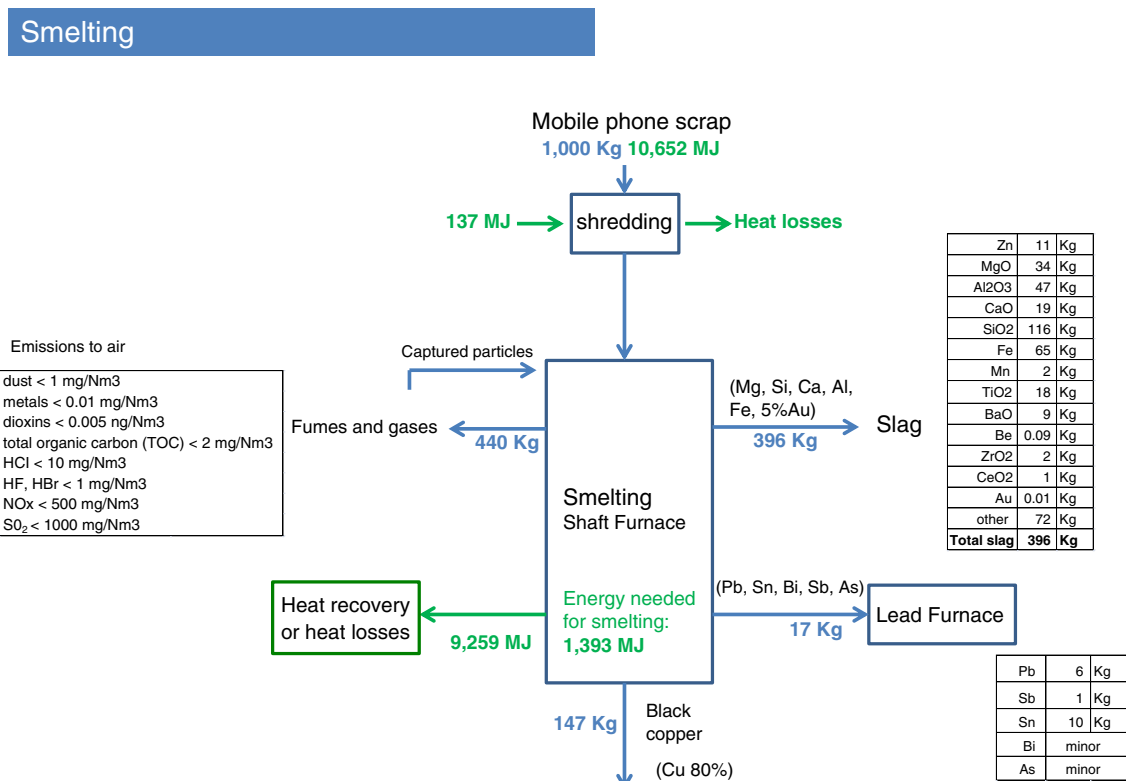


Fig. 2 Smelting phase substances and energy flows for 1 tonne of mobile phone waste

the emissions of both the anode furnace and the electrolytic refining as a sum.

Anode casted plates are submerged in an electrolytic bath. The electrolyte is an aqueous solution of 180 kg sulfuric acid per cubic meter, which is continuously renovated at a rate of 0.2 m³/kg of refined copper (Classen et al. 2009). Copper deposits on the cathode plates result in 128 kg of 99.99 % Cu, while nickel with some impurities dissolves in the electrolyte. This electrolyte is then purified to recover nickel (15 kg) with minor impurities. The rest of the anode impurities, mainly the precious metals, precipitate at the bottom of the bath and are collected as anode slime mud (5.41 kg). The average power consumption for the electrolysis is around 350 kWh/tonne of refined copper (Davenport et al. 2002), which means 161 MJ for 1 tonne of mobile phones. Emissions to water are calculated from Ecoinvent (Classen et al. 2009).

4.3 Hydrometallurgical route

Black copper from the smelter is granulated and sent to the leaching–electrowinning plant. Copper is leached with sulfuric acid to produce a copper sulfate (CuSO₄) solution that is used to fill the electrolytic cells. The electricity required is quite high because a comparatively high voltage is needed (3 V), compared to the electrorefining (0.2–0.3 V). During electrowinning, copper migrates to the cathodes, and precious metals are collected in the leach residue for further processing

in the precious metal refinery. Assuming that the energy consumption is similar to conventional electrowinning of copper, we use the value of 2,791 kWh/tonne of Cu refined given by Alvarado et al. (2002). This might be somewhat higher than the energy required for electrowinning the mobile phone waste, since this figure is based on an average ore grade of 1.14 %, and the copper content in shredded mobile phones is greater. Based on 128 kg of refined copper, we estimate 1,424 MJ/tonne of mobile phones during electrowinning.

4.4 Precious metal refining

Since the material recovery rates are similar between the two routes (Huisman 2004; Keller 2006; Legarth et al. 1995), we consider that the composition of anode slimes from electrorefining and leaching residue from electrowinning is the same. According to recovery rates described above, anode slimes resulting from processing 1 tonne of mobile phone waste contain 3.63 kg of silver, 0.347 kg of gold, 0.15 kg of palladium, 1.3 kg of copper, and other minor impurities.

The treatment of these anode slimes differs greatly from plant to plant, but in general follows five steps: decopperization, recovery of selenium and tellurium, silver extraction, gold extraction, and finally refining of platinum group metals (PGM). The first two steps can be accomplished by different processes such as roasting, sulfation, and cupellation among others (Renner 2008). For example, copper can be extracted by

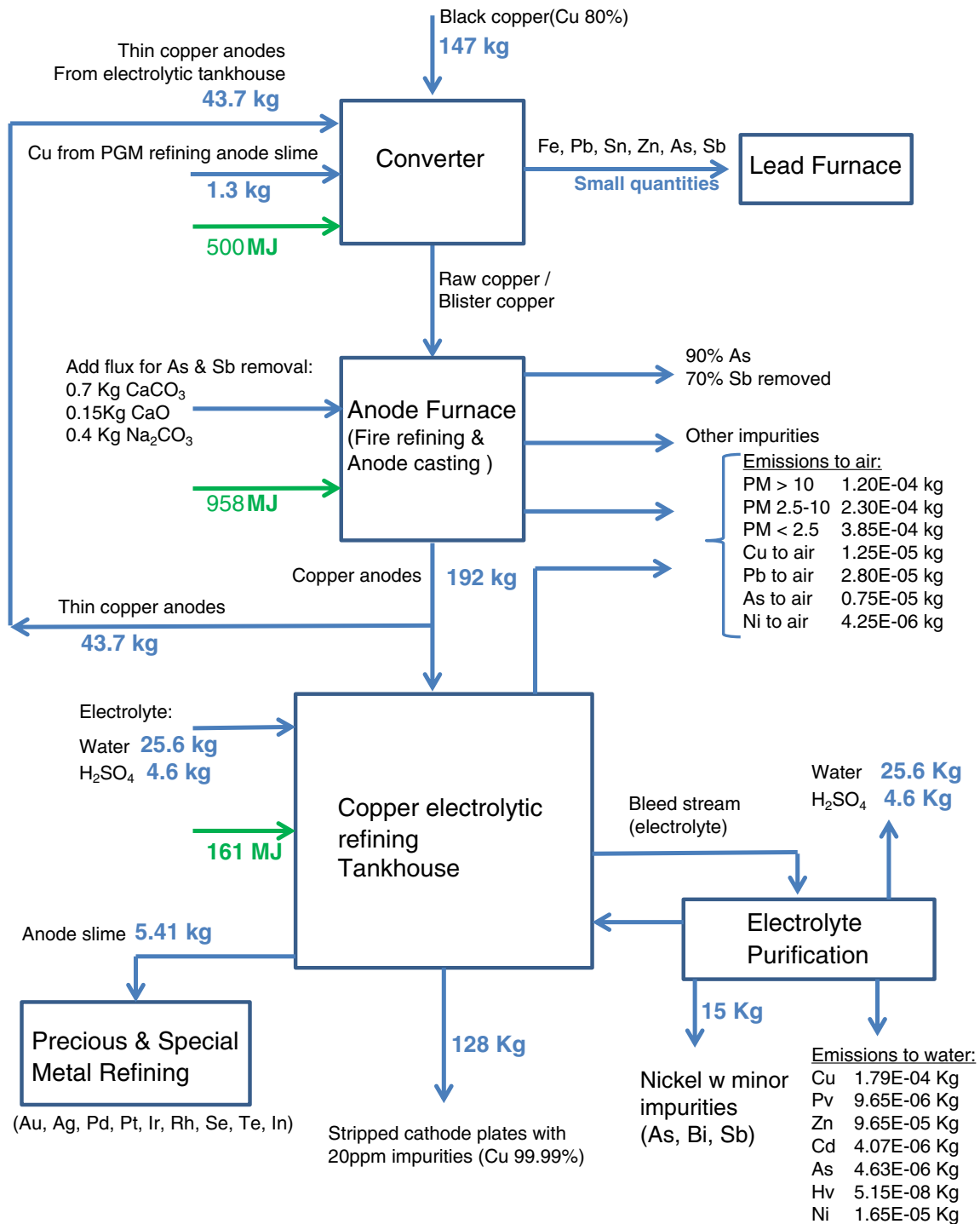


Fig. 3 Boliden converter–anode furnace–electrolytic refining substances and energy flows

leaching in a solution of 250 g/l sulfuric acid, under pressure (3–7 bar), and at elevated temperature of 115 °C and in the presence of a 10 % sodium chloride to prevent silver from dissolving. The energy needed for this step is 1,788 MJ/tonne of mobile phones (Battelle 1973b). A part of this decopperization, selenium and tellurium have to be recovered as they interfere with precious metal refining. Mobile phones do

not contain selenium and tellurium, but if they are mixed with scrap containing these metals, the slimes will have to go through these processes.

After these two initial processes, the remains of the slimes are smelted and casted to silver–gold–PGM alloy anodes called dorée bullion. Then silver is extracted from the dorée anodes by electrolysis in nitric acid. There are several

processes to refine silver but the most commonly used in Europe is the Mobius (or Moebius) electrolysis. The energy consumption is 485 MJ/kg of refined silver (counting only the dorée refining and electrolysis) (Battelle 1973b), which translates to 1,761 MJ for the extraction of 3.63 kg of silver from 1 tonne of mobile phones. The residue of the electrolysis is melted and casted again and sent to further electrolytical refining to recover the gold. The electrolyte used in this case contains 2.5 mol/l of hydrochloric acid and 2 mol/l of tetrachloroauric acid at 65–75 °C (used by the Wohlwill process and resulting in 99.99 % purity (Renner et al. 2005)). An energy consumption of 186 MJ/kg of refined gold is estimated for average ore grades from US mines for the electrolytic refining, melting, and casting (Battelle 1973a), which can be recalculated to 65 MJ/tonne of mobile waste based on 0.35 kg of gold obtained in these operations. The remaining slime consists mainly of PGM that is recovered by a fractional precipitation process.

The Umicore Hoboken plant consumes 64,120 MJ/kg of PGM produced from e-scrap, which consists of 400 g of platinum, 510 g of palladium, and 90 g of rhodium (Saurat 2006). This figure includes the energy requirements for all operations from the smelter until the PGM refining. Based on 150 g of PGM recovered from 1 tonne of mobile waste and subtracting the energy consumption of all stages except for PGM refining, we allocate 3,180 MJ/tonne of mobile phone waste processed for PGM production. When we add all stages from smelting until PGM refining, this results in a total energy consumption of 9,748 MJ/tonne of mobile phones. This figure seems too high when we compare it to the total energy consumption of 7,431 MJ/tonne of mobile phones (including smelting all the way to precious metal refining) that Umicore quotes specifically for mobile phone recycling (Hagelüken 2006). We will use the latter for our energy balance, because although both figures are given by Umicore, the latter is specific for mobile phones. Thus, 7,431 minus 6,431 MJ (which is the sum of the energy required by smelting, electrolytic refining, and silver and gold refining) results in 1,000 MJ/tonne of mobile phones allocated to PGM production.

Process data for the refining of precious metals is not readily available to complete the material balance with the appropriate amounts of acids needed. Furthermore, the estimates we have provided here for the energy requirements of gold and silver are based on precious metal processing from ores. Although the unit operations are the same, the composition of the input can vary. We are aware of the uncertainty introduced by some of these methods for quantifying the MFA, but given data confidentiality, it is better to have some estimate than none at all.

5 Results

Material recovery rates for copper, gold, silver, PGMs, nickel, lead, antimony, and tin are all in the order of 80–99 %,

resulting in the following recovery of these metals from 1 tonne of mobile phones: 0.347 kg of gold, 0.15 kg of palladium, 3.63 kg of silver, 128 kg of copper, 15 kg of nickel, 6 kg of lead, 1 kg of antimony, and 10 kg of tin. Other materials such as rare earths, gallium, or niobium are not being recovered at present time. During the process, 440 kg of plastics is combusted, and 396 kg of slag is obtained and typically sold for reuse as construction material. The total energy needed for the pyrometallurgical route is 7,763 MJ/tonne mobile waste, whereas for the combined pyrometallurgical and hydrometallurgical, we estimate a total energy consumption of 7,568 MJ/tonne mobile waste. According to Umicore, the total energy contained in the plastics of 1 tonne of mobile phones is 10,652 MJ (Hagelüken 2007), resulting in a positive energy balance of 3,221 MJ that can be sold or used for other processes in their plant.

How do the energy and material consumption of the recycling processes compare to that of primary production? One of the first things we realize is that the copper content of the mobile phone waste is 8.7 to 14.2 %, while the ore grade average for copper is 0.99 % (Kippenberger 2001), ranging from 0.55 % for North America and 2.63 for Africa (USBS 1987). It follows then that more energy is required for primary production. If we normalize the energy and material consumption of the pyrometallurgical and the combined recycling processes excluding the precious metal recovery, we estimate 23,125 and 22,007 MJ/tonne of refined copper, respectively. Primary production energy requirements can vary depending on ore grade, transport, and fuel type used, among others, even for the same technology. There are several studies that quantify the cumulative amount of primary energy consumed in all stages (mining, processing, and metallurgical operations), also known as gross energy requirement (GRE). These estimates range considerably from 33,000 MJ/tonne of refined copper (Norgate 2004), 45,000 MJ/tonne (Mudd 2010) and 46,800 MJ/tonne (Kippenberger 2001) for smelting/electrorefining, and up to 64,000 MJ/tonne for heap acid leaching/solvent extraction and electrowinning (Norgate 2004). Norgate has estimated a potential 84 % energy savings from secondary copper production (not including collection, transport, and separation of metallic products containing the copper). These estimates are summarized in Table 2.

As far as materials are concerned, recycling offers the obvious advantage of not having the mine waste associated with primary production, which is estimated to be 261 tonnes of mine waste, 145.3 tonnes of ore, and 127.5 m³ of waste water per tonne of copper refined (Kippenberger 2001). Furthermore, the pyrometallurgical route requires less H₂SO₄ because it excludes the electrowinning operation, which consumes 2,103 kg H₂SO₄/tonne of refined copper (Ayres et al. 2003). The electrolytic refining process also requires H₂SO₄, but in much smaller amounts: 36 kg/tonne of refined copper in our case, which is similar to the

Table 2 Comparison of energy requirements for recycling and primary production of certain metals recovered from mobile phones. Note: recycling estimates only include process requirements (excludes

collection and sorting of mobile phones), while primary production includes mining energy requirements and excludes transportation

	Recycling from mobile phones		Primary production		
Copper (MJ/tonne)	23,125	Pyrometallurgical	33,000	Pyrometallurgical	Norgate 2004
	22,007	Hydrometallurgical	45,000		Mudd 2010
			46,800		Kippenberger 2001
			64,000	Hydrometallurgical	Norgate 2004
Silver (MJ/kg)		980	1,155	As by-product from copper production	Battelle 1973a
Gold (MJ/kg)	19,322	18,765	34,228	Open-pit mining	Battelle 1973b
			150,000		Dominguez 2012
PGM (MJ/kg)		64,120	167,600		Mudd 2010
			254,600		Mudd 2010

electrolytic refining step of primary production. Slag generation is also greater for primary production, with values ranging from 1,900 kg (Kippenberger 2001) to 2,952 kg slag/tonne of copper refined, whereas our study shows that the smelting of mobile phones produces a slag of 396 kg/tonne of copper refined.

The same type of comparison can be done with the production of gold, silver, and other metals. Silver production from copper anode slimes (from copper primary production) requires 1,155 MJ/kg silver refined, which includes leaching, roasting, and filtration with H_2SO_4 , doré refining, and electrolytic parting (also needing H_2SO_4), melting, and recasting. Our study shows a comparable figure—980 MJ/kg of refined silver. This is calculated by summing 1,788 MJ from cupellation and 1,761 MJ from doré and electrolysis silver refining for 1 tonne of mobile phones, divided by 3.63 kg of silver refined. It is safe to say that, in general, the precious metal refining energy and material requirements will be very similar for their extraction from mobile phone waste and as by-products from primary metal production. In this respect, it is really in the copper recovery process where we see great savings in both energy and materials.

However, if we compare the recycling of precious metals from mobile phones to their production directly from ores, the energy required is much less. For example, let us take gold. Based on an ore grade of 0.001 %, an estimate of 34,228 MJ/kg of refined gold from open-pit mines is given by (Battelle 1973a), which includes crushing and grinding, leaching, thickening, clarification and purification, melting, casting, electrolytic refining, and further melting and casting. The chemicals needed are chloride, soda ash, lime, and sulfuric acid to name a few. More recent sources cite quantities as large as 150,000 MJ/kg refined gold due to decreasing ore content in world mines (Dominguez and Valero 2012). Our calculations, based on 0.35 kg of refined gold from 1 tonne of mobile phones (including operations from shredding of the mobile

phones to final gold casting), result in 19,322 MJ/kg of refined gold for the pyrometallurgical process and 18,765 MJ/kg of refined gold for the combined hydro- and pyrometallurgical processes (see Table 2). For PGM recovery from shredded mobile phone waste, we quoted 64,120 MJ/kg of PGM for Umicore—more than ten times less than that estimated from PGM-bearing ores, which can range from 167,600 to 254,600 MJ/kg of PGM on average (Mudd 2010).

The comparison of energy requirements between recycling and primary production is not so straightforward, and some further considerations need to be taken. For example, mobile phone manufacturers might use a mixture of primary and secondary metals. Without additional industry information regarding the source of the materials, it is impossible to properly allocate environmental burden. Furthermore, the energy savings illustrated here do not include the collection, transportation, separation, or further preprocessing of electronic scrap necessary prior to shredding and recycling. Given the diversity of used mobile phone collection schemes, some of these stages are very difficult to quantify and very location-specific. Even so, Bigum et al. (2011) found that the pre-recycling sorting processes (manual, optic, magnetic, etc.) had very little environmental effect compared to the metallurgical treatment for copper, gold, nickel, palladium, and silver recovered from Waste Electric and Electronic Equipment (WEEE). For these metals, recycling showed savings in all LCA categories compared to primary production (Bigum et al. 2011). Similarly, another study found that collection and preprocessing contribute only marginally to environmental impacts of electronic waste material recovery. In addition to pre-recycling treatments, there are other processes that need to be considered such as the disposal of the plastic fraction of the mobile phones. Umicore incinerates the plastic to provide the energy required for the smelting; however, a Japanese study showed that the CO_2 emissions generated by the incineration of plastics were

almost the same as those avoided by recovering the metals (Takahashi et al. 2009a, b).

6 Conclusions

The study presented in this paper presents a MFA and energy requirements for recycling 1 tonne of used mobile phones in which gold, palladium, silver, copper, nickel, lead, antimony, and tin are recovered (between 80 and 99 %). The two main industrial processes used at the present time (pyrometallurgical and combined pyro-hydrometallurgical) have similar energy consumptions (7,763 and 7,568 MJ/tonne of mobile phones, respectively). An average tonne of used mobile phones represents a potential of 128 kg of copper, 0.347 kg of gold, 0.15 kg of palladium, 3.63 kg of silver, 15 kg of nickel, 6 kg of lead, 1 kg of antimony, and 10 kg of tin as well as other metals that are not yet profitable to recover but might be in the future. Current industrial processes do not recover other scarce materials such as rare earths, niobium, or gallium because of physical limitations and because it is not economically viable to do so, at least not with current metal prices. Other technology products that use these metals such as wind turbines, electric vehicles, and new generation solar panels will probably change their demand and influence prices in the near future (Talens Peiro et al. 2012).

Life cycle analysis studies show that the impact of the production stage of the total energy consumed in the life cycle of a mobile phone is between 60 and 80 % (Andrae and Andersen 2010), of which gold extraction and production is responsible for 10 to 35 % (Singhal 2006). Recovering and recycling the metals from mobile phones could potentially reduce this impact as a result of lower energy requirements. We have shown that the energy consumption for producing refined copper from mobile phones (22,007 to 23,125 MJ/tonne of refined copper) is about half of the energy necessary for primary production (45,000 to 46,800 MJ/tonne of refined copper, depending on the ore). Besides avoiding the large amounts of waste associated with mining and ore extraction, the acids needed and the slag produced are also lower for recycling copper from mobile phones than for primary copper extraction.

Comparison of the materials and energy required for the refining of the precious metals from primary metal extraction versus mobile phone recycling is not as straight forward for several reasons: (1) not enough information is available due to data confidentiality of industry, and (2) since these metals are by-products of primary metal extraction, allocation of energy and material needs is not always clear. We have provided some figures to illustrate the potential energy savings that recovering precious metals from mobile phones offers against precious metal-bearing ore extraction. For example, 34,228 MJ/kg of refined gold are required for open-pit mines,

with an ore grade of 0.001 %, whereas our study allocates between 18,765 and 19,322 MJ/kg of refined gold from mobile phone waste.

Considering that only 2.5 % of used mobile phones are presently being recovered for material recycling and 50 % are simply kept in the drawer (Hagelüken and Buchert 2008), the energy and material savings potential from recovering a larger fraction of cellular phones is tremendous. We hope that the results of this study will provide the incentive to increase the recovery rate of mobile phones. One important drawback of the current technologies is that the pyrometallurgical route requires large infrastructures such as integrated smelters and is only economically feasible at large scales. For example, the recovery facility of Umicore in Hoboken needed an investment of over US\$1 billion (Hagelüken 2006). During the last decade, research has focused on hydrometallurgical methods that avoid the high operating costs of smelters but only at small scales, and only one metal is recovered, such as gold (Cui and Zhang 2008).

The last revision of the European WEEE directive on July 2012 asks that 50 % of the small electronic waste generated be recycled by 2015 (and 55 % thereafter). However, due to the fact that used phones are mainly stored at home, there is large fraction of generated waste (and potential urban mine) that is difficult to quantify. We propose that more efforts are placed on increasing the recovery of used mobile phones in order to maximize energy and material efficiency.

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